STRESSES MADE VISIBLE

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This age has been variously described as the age of steam, of iron, and of electricity; but maybe it is better described as the age of stress and strain. We are constantly surrounded by stresses capable of destruction, which are restrained only by our engineers. Our silent guardian is "safe stress."

Economy and safety are of prime importance in engineering. The designer, therefore, faces a difficult problem. He has to design construction members and parts of machinery in such a way that they will be just strong enough. In order to do that, he must determine the existence and distribution of the various stresses.

There are two principal methods: (1) The theoretical method which uses the equations of elasticity and is mathematical in character. (2) The experimental method where the stress-distribution is determined by direct measurement. Both methods have their difficulties. The first one gives accurate enough results, but only in a few simple cases where mathematical methods are possible. For odd-shaped members certain assumptions and estimations will introduce a great error. The second method has been worse off and impractical even in simple cases until 1920 when Dr. E. G. Coker of the University of London first developed the method of stress-determination now known as Photo-Elasticity.

The name "Photo-Elasticity" is composed of two words: "Photo" and "Elasticity." The origin of the word "photo" is the Greek word "phos" which means "light." "Elasticity" does not refer to the elasticity of light, but indicates that the method is based on the theory of elasticity.

THEORY OF PHOTO-ELASTICITY

Certain singly refracting materials such as celluloid, bakelite, and others become doubly refracting when they are subjected to deforming loads; the double refraction varies with the strain conditions. These deforming loads produce a redistribution of molecules; e.g., in the direction of a tensile stress of a bar an elongation takes place and the particles are pulled farther apart and vice versa. In short, the material becomes a "temporary crystal". From what we have learned about double refraction, it is clear that when plano-polarized light is passed through, it leaves the specimen as two beams of plano-polarized light with the planes of polarization perpendicular to each other. These two beams vibrate at different velocities in the medium since the "resistance" is not the same in all directions. This produces a phase difference between the two waves, which will stay constant after they leave the medium. This phase difference depends on the displacement of the particles, i.e., upon the stress condition and upon the thickness of the material.

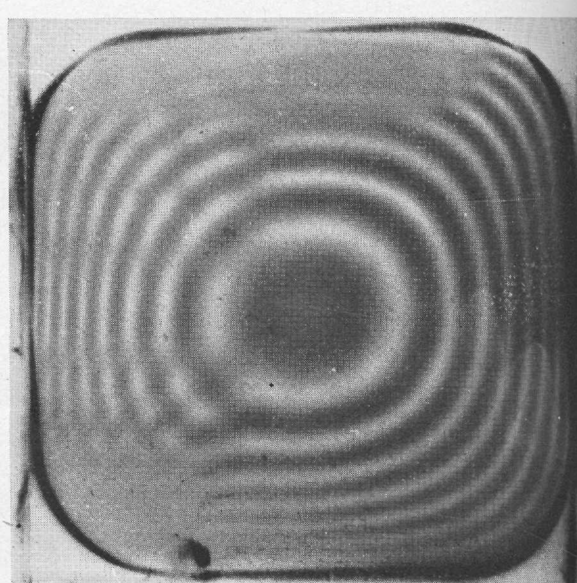
This is the fundamental equation of Photo-Elasticity. Expressing it mathematically:

$$R=cLt^{7}$$

This simply means that the retardation is proportional to the strain and the thickness of the material.

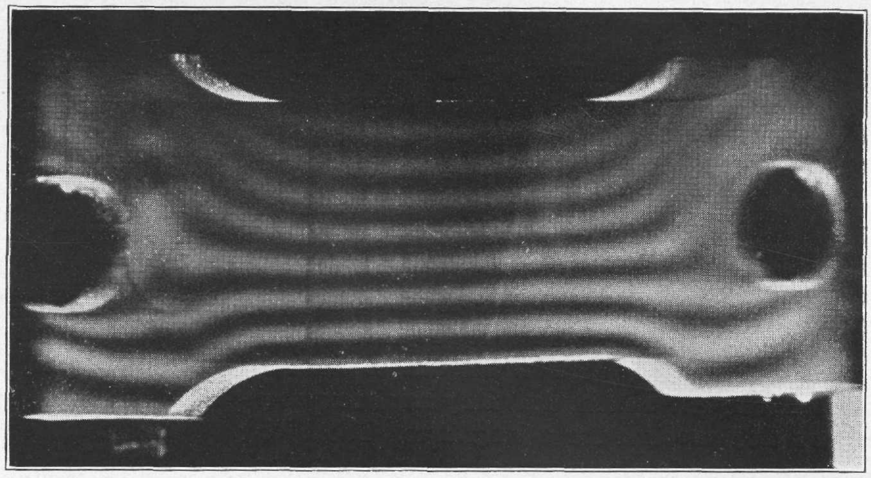
Here now is the important point: Assuming a constant thickness, the retardation will be the same along lines of equal stress. These lines can be made visible by a phenomenon known as interference.

There are three kinds of stresses: (1) Tension, (2) Compression, (3) Shear. In even simple cases the total stress consists of a mixture of all three and varies from point to point in a plane and from plane to plane at a point. The maximum shearing stress along a plane at a given



Fringe Pattern of Shaft in Torsion

Courtesy of Engineering Experiment Station



Fringe Pattern for Specimen in Tension

Courtesy of Engineering Experiment Station

point is equal to one-half the difference of the principal stresses (tension and compression) at that point.

The strain produced by this maximum shearing stress is proportional to the retardation and is therefore indicated by the photo-elastic method. Also, by a coincidence, materials are weakest in shear, which means that the amount of shear they can carry without failing is much smaller than the maximum amount of tension or compression which they can carry without exceeding the elastic limit. This fact accounts for the tremendous importance of the photo-elastic method.

In review of the theory we can therefore state that the maximum shearing stress in a test piece can be found by measuring the difference in phase of the two vibrations of polarized light. To do this, the vibrations are brought into interference in the same plane.

INTERPRETATION OF DATA

If monochromtaic light (i.e., light of only one color) is used, the unstressed specimen will show off dark since there is no strain, no retardation, and consequently the two vibrations will cancel each other due to interference. As soon as stress is applied, the area will gradually brighten up and the stress distribution will become visible. As the stress is increased, a point will become bright and dark alternately, and the number of fringe will increase in a given area, which indicates a higher stress.

The number of cycles a point undergoes in changing from bright to dark and back to bright is called the fringe-order. Another concept, which is very important, is the fringe-value. It is obtained from a standard beam, which is subjected to a certain load. The stress can be calculated very easily and the fringe can be given a certain stress value as a basis of comparison.

DEVELOPMENT OF THE METHOD

Ever since David Brewster in 1816 accidentally discovered double refraction, Photo-Elasticity has gone a long way. The outstanding pioneers were Henry Favre in France and Dr. Ernest G. Coker in England. The method was introduced into the United States in the early twenties. Industry was quick to realize the immense possibilities and soon an organized program of research was started.

From a plaything Photo-Elasticity has developed into an exact mathematical science.

The latest development — "Three-dimensional Photo-Elasticity"—was invented by an Ohio State graduate, Dr. Royal Weller, and first published in his doctor's thesis in 1939. It is still in the experimental stage, although a very complicated theory has been compiled on it, due credit going to the Ohio State Engineering Experiment Station. This new method permits the determination of stresses in test-pieces of non-uniform thickness at any point in the interior.

THE TECHNIQUE OF PHOTO-ELASTICITY

Photo-Elasticity has already contributed greatly in stress-analysis and proved its value in the field of engineering. A lot of the success of the method, however, depends on using the right technique.

The apparatus used for testing is called a polariscope. It consists usually of a monochromatic light source, a mercury-vapor lamp, which emits blue light, with a yellow filter. A lens-system is used for focusnig the light rays, while the actual photo-elastic equipment consists of a polarizing disc, a strain frame which holds the test specimen, and the analyzer. The stress-

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and should be supplemented by photo-elastic pictures. Professor Frocht, a noted educator, expresses this need very aptly: "The photo-elastic method is the method which makes stresses, their formation, growth, and intensity visible to the naked eye".

Enough has been mentioned in this paper already to demonstrate that Photo-Elasticity has not only established itself as a science, but also as a very practical means of helping in building the progress of civilization.

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pattern is either produced on a screen or photographed with a camera.

Great care has to be taken in the preparation of the test specimens. Bakelite is the most common material. After having been polished to make them as clear as window glass, the slabs are very carefully annealed to remove all internal stresses. They are then accurately cut to represent a miniature model of the machine or construction member about which information is desired. Results on models represent the actual conditions in structural materials which are homogeneous and isotropic. Obviously, this classification does not fit wood, which is fibrous.

VALUE OF THE PHOTO-ELASTIC METHOD

Turning now to a full evaluation of the advantages of the photo-elastic method, we can see how greatly it benefits us. It has taught us many important facts about stresses, e.g., it has shown us that a stress-concentration exists at sharp corners and around holes, that such stress-concentrations cause cracks which ultimately lead to the failure of the structure, and therefore are dangerous. By good design the engineer can eliminate them and provide a "safe stress." It can be understood now how a $10 test can prevent $1,000,000 of damage, how it can save tremendous sums in design-economy, and how it can protect our lives from forces of destruction.

Another important aspect is the part played by Photo-Elasticity in engineering education. In a course on strength of materials instruction could